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ABSTRACT

The upcoming lower temperature/higher energy upgrade to the Fermilab Tevatron accelerator has raised questions concerning peak pressures during magnet system quenches. An experiment was performed to measure the pressure versus time at various quench energies in several devices in the Tevatron. A smaller study also looked at the temperature and mass flow rate versus time.

Data was captured in a PC based circular buffer. The buffer captured ten seconds of data at 250 Hz for up to eight channels. Quenches ranging from 400 GeV to 1000 GeV were investigated. Peak pressures of 1.24 MPa (180 psia) were measured at 1000 GeV. Peak pressure increased linearly with quench energy up to 950 GeV, where it flattened off. Likewise, the time to reach peak pressure decreased linearly until 900 GeV, where it flattened off at 280 ms.

The process appears to become heat transfer limited at about 900 GeV. This results in reasonable peak quench pressures at the expense of the coil reaching higher peak temperatures (not measured). The existing cryostats and relieving systems in the Tevatron will be sufficient for the new low temperature upgrade.

INTRODUCTION

Plans are underway to increase the energy of the Tevatron superconducting accelerator.¹ Currently the Tevatron operates at 800 GeV and 900 GeV during fixed target and colliding beam physics, respectively. The initial goal is to raise the energy by 100 GeV in each mode of physics. The ultimate limit for the system will be 1100 GeV in colliding beam physics. It is expected that a series of weak magnet identification and replacements will be necessary to achieve 1100 GeV.

The Tevatron is cooled by twenty-four satellite refrigerators. Each refrigerator cools two 125m long magnet strings. Typically there are two cells per magnet string. A half cell consists of four dipole magnets for bending the beam, a quadrupole magnet for focusing, and a spool piece. The spool piece is a catch all device that contain such things as correction elements, quench stopper, temperature and vacuum instrumentation, and a vacuum break. Electrically, the smallest unit in the Tevatron is a cell. Should a magnet quench (when the superconductor goes normal) the quench protection system fires heaters in the dipoles of the cell. This spreads out the absorption of the stored electrical energy of the magnets to prevent conductor burnout.

* Operated by Universities Research Association, Inc. under contract with the U.S. Department of Energy

Each 7m long superconducting dipole in the Tevatron is protected from over pressurizing during a magnet quench by a quench relief valve. The relief valve is mounted external to the magnet at room temperature. A 3 cm tube runs from the 4.5K liquid helium reservoir at one end of the dipole out to room temperature. A check valve located at approximately the 20K point in the tube helps to prevent thermoacoustic oscillations in the tube. The outlet of the relief vents to a 21 cm header. This header serves as both the compressor suction and quench header. It leaves the accelerator tunnel every 250m where it is relieved to atmosphere by a 21 cm 0.14 MPa (20 psia) parallel plate relief valve.

There were concerns that increasing the energy of the Tevatron would increase the peak pressures in the liquid helium passage beyond the yield point of the weakest component. A rectangular box in the spool piece that houses the quench stopper has been identified as the weakest component, yielding at a pressure of 1.45 MPa (210 psia) near liquid helium temperatures. Extrapolating existing data with energy suggested peak pressures of 1.62 MPa (235 psia) were possible. As a result this study was performed to better understand the quench characteristics of the Tevatron, particularly at lower temperature and higher energy.

TEST SETUP

Out tests were performed at the A2 refrigerator of the Tevatron. Since the tests were performed on an operational machine, we were forced to install all our instrumentation externally at room temperature. The cell chosen was A24, which covers all the components from A23 to A25. To ensure that we did not see end effects, we chose to instrument components in the middle of the quenching cell at A24. Various tests were performed utilizing instrumentation on the spool piece at A24 and the first dipole on each side of the spool.

The speed at which a quench event takes place is such that the existing Tevatron controls system could not be used for data acquisition. A PC with an eight channel data acquisition board was used as a standalone system. Data for each channel was continuously collected in a 10 second circular buffer. The first channel was the quench bit from the Quench Protection Monitor (QPM) which indicated when the quench occurred. This channel was used to stop the circular buffer to capture the data. Timers were used to stop the circular buffer eight seconds after the quench was detected. This resulted in two seconds of data preceding the quench and eight seconds after. Data was collected at 250 Hz (4 ms) per channel. This gave us adequate resolution for the event which typically peaked out near 300 ms.

Since we were limited to seven channels (plus the quench bit), we varied the instrumentation from which data was collected from quench to quench. The behavior of a given device was very repeatable for multiple quenches of the same energy. As a result, we feel confident mixing data from different quenches of the same energy to effectively have more channels of data. Ten pressure and two temperature measurements were investigated. Figure 1 shows a modified relief valve that contains eight of the twelve sensing points used.

Early tests focused on two pressure measurements: the relief valve inlet pressure (P1 in Figure 1) and the pressure measure on the spool piece correction magnet power lead flow (P7). The former had the advantage of a very quick response. Although the latter responded more slowly due to flow resistance up the power lead, it gave a more accurate reading of peak pressure internal to the magnets. There was a small flow fixing orifice for the power leads downstream of the pressure reading. However, for an event as fast as a quench, we feel that this pressure measurement looked to be single ended. As a verification, the pressure difference between P7 and P1 at the pressure peak reasonably agreed with pressure drop calculations for the 3 cm diameter by 60 cm long tube between the magnet coil and the relief valve.

The original goal was to find the peak quench pressure versus energy. Our interest in trying to better understand the process led to the instrumentation shown in Figure 1. The body of the relief valve was modified to add four pressure sensing locations. A section was added downstream of the valve that incorporates a Pitot tube and thermometry for the mass flow rate measurement.

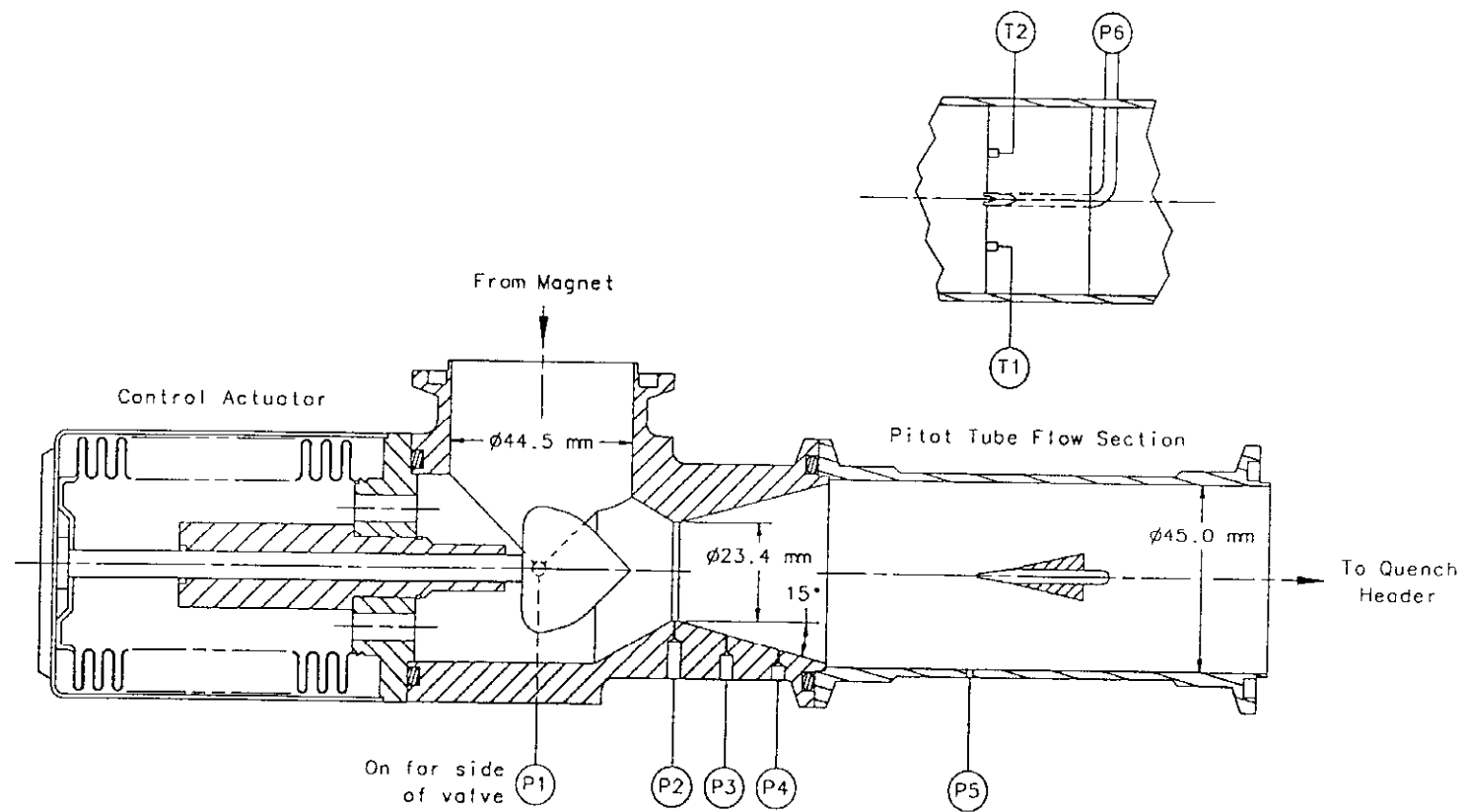


Figure 1. Instrumented quench relief valve

Considerable care was taken to minimize resistance and capacitance in the measurements. All pressure tap holes were free of burs. A very small hole (0.34 mm) was used on P2, 3 and 4 to minimize flow effects. Each of these was backed up by a larger diameter hole to within 2 mm of the surface to minimize resistance. Temperature measurement at the Pitot tube was accomplished using Lake Shore Cryotronics, Inc., DT-470-SD series silicon diodes. They were chosen for their small size, ruggedness, and fast response. Each one was lightly epoxied to the knife edge of a G-10 wedge located at the Pitot tube. Table 1 lists the primary instrumentation used.

TEST RESULTS

Quench Pressure Measurement

With the existing satellite refrigerator operating temperatures (4.45K) the Tevatron can achieve a peak energy of 930 GeV. Therefore special provisions were made to achieve 950 and 1000 GeV quench data. We used prototype cold vapor compressors to lower the temperature to 3.92K. Since we only had enough equipment to cool one sector (one sixth of the Tevatron), that sector had to be electrically isolated from the others and powered separately. Considerable study time was necessary to obtain these higher energy quenches. Quenches at 900 GeV or below were relatively easy to schedule, requiring one hour to recover from the quench.

Quench pressure (P7) versus time is shown for Tevatron energies ranging from 400 to 1000 GeV in Figure 2. The quench is detected by the QPM at time equal zero. It takes a finite amount of time for the heat to get into the helium and pressurize the circuit to the relieving set point of 0.31 MPa (45 psia). For a 1000 GeV quench, the relief valve opens about 70 ms after the quench was detected. For a 400 GeV quench it took 250 ms. (Note that these times cannot be found accurately in Figure 2 due to the additional flow resistance of sensor P7 described earlier.)

Peak pressure increased linearly with Tevatron energy until 950 GeV. At that point the increase in peak pressure was considerably reduced. Similarly the time it takes to reach peak pressure linearly reduced with energy until 900 GeV, at which point it remained constant at 280 ms. The process appears to become heat transfer limited at about 900 GeV. This results in reasonable peak quench pressures at the expense of the coil reaching higher peak temperatures (not measured). The existing cryostats and relieving systems in the Tevatron will be sufficient for the new low temperature upgrade. Peak pressures reached at 1000 GeV were 1.24 MPa, below the 1.45 MPa yield point of the spool piece.

Relief Valve Oscillations

During our studies, we noticed a high frequency oscillation as the pressure reduced to the 0.31 MPa (45 psia) set point of the relief valve. A good example of this phenomena is shown in Figure 3 for a 900 GeV quench. This figure shows the relief valve inlet pressure (P1) versus time. The time scale has been expanded to show all the data of the circular buffer; two seconds before and eight seconds after the quench.

Table 1. Primary instrumentation description

T1	Helium temperature at Pitot tube
T2	Helium temperature at Pitot tube (spare)
P1	Relief valve inlet pressure
P2	Relief valve throat pressure
P3	Diverging nozzle, 12.7 mm from throat
P4	Diverging nozzle, 25.4 mm from throat
P5	Pitot tube static pressure
P6	Pitot tube total pressure
P7	Spool piece correction magnet power lead flow pressure

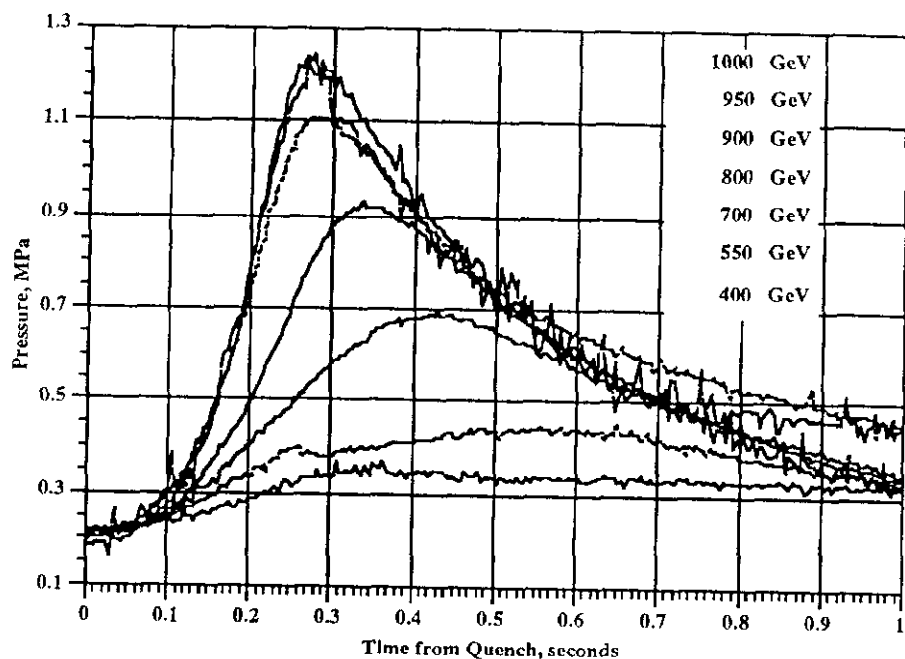


Figure 2. Quench pressure versus time. Curves in the vicinity of their peak correspond to the legend order.

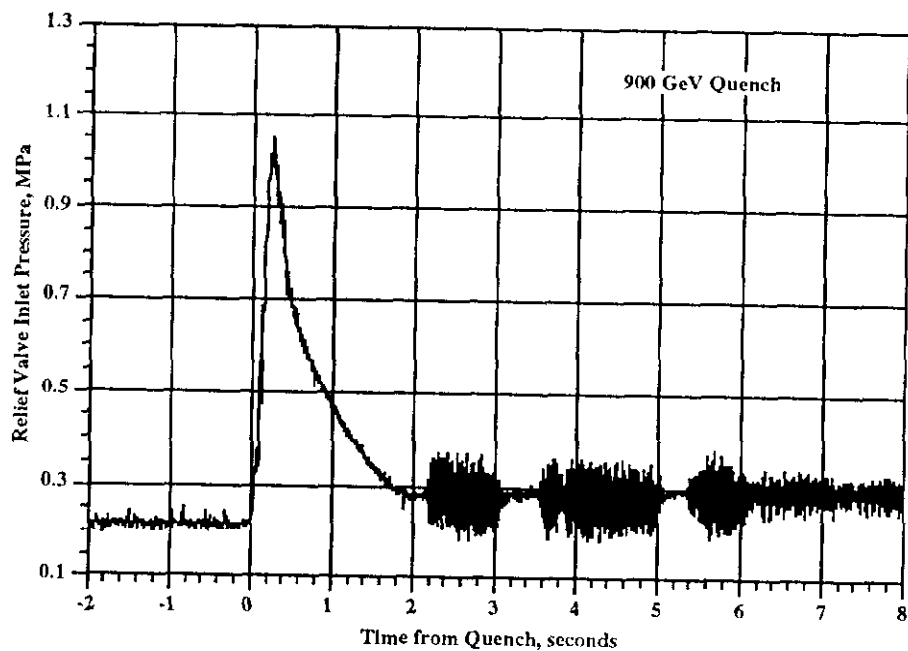


Figure 3. Relief valve inlet pressure versus time showing valve oscillations on reclosure. Relief valve set point is 0.31 MPa.

This figure clearly shows a fluttering of the relief valve about its set point beyond its time of two seconds. The fluttering comes and goes as is evident by the quiet periods from 2 to 2.6 second and again from 5 to 5.4 seconds. We expanded the data in order to attempt to reveal the frequency of the oscillation. Unfortunately, the 250 Hz sample rate was not high enough to define the oscillation.

Late in our testing we purchased a new A/D board to regain a channel that had failed. The new board was improperly setup when it was installed, resulting in one second of data being taken at 2500 Hz instead of ten seconds at 250 Hz. We were fortunate to have the one second of captured data be during the fluttering. At the higher sample rate the oscillation was clearly defined at 95 Hz.

We carefully measured the mass of the bellows, shaft and poppet of the relief valve as well as the spring constant of the bellows to predict its natural frequency. An equation for natural frequency was used which considers a lumped mass on a spring with mass.² The resulting natural frequency was 47 Hz. The valve was therefore oscillating at its second harmonic.

This high frequency oscillation explained a problem we have experienced over the last ten years. We have had many failures (cracking) of the control actuator bellows at the end closest to the valve poppet. One such valve, which had experienced only one quench, was sent out for metallurgical analysis. The report concluded that the bellows had experienced at least 1600 cycles! It was later verified that low amplitude, high frequency oscillations would be capable of causing the failure.

Mass Flow Measurement

The mass flow rate was measured using a Pitot tube and temperature sensors downstream of the relief valve. A fair amount of noise was experienced, as would be expected, on the Pitot tube total pressure measurement. The silicon diode temperature sensors required 130 ms to cooldown, from the time the relief opened (70 ms after the quench) to 200 ms. At that point the diode read a relatively constant 22K over the time of interest for relieving (<1 second). As a result, a constant 22K was assumed for the entire relieving period in order to calculate a mass flow rate.

Figure 4 shows the results of the mass flow measurement for a 900 GeV quench. The results were numerically integrated to yield a total mass relieved of 1023 grams. Since the tests were performed in the middle of a quenching cell, one would expect the mass relieved to only represent one dipole magnet. As it turns out, the measured relieved mass represents 56% of the helium in one dipole. This is however a reasonable representation of the helium which is in contact with the superconducting coils (61%). The remaining 39% is somewhat isolated from the coils, located outside the stainless steel collars heat exchanging with the concentric two-phase helium. It is possible that the majority of this helium is also relieved, except over a longer period of time (10s of seconds) as heat reaches this area. This theory is reinforced by measurements made of the two-phase circuit during a quench in which the two-phase pressure had not peaked by the end of our data collection (8 seconds).

ANALYSIS

As one would expect, the relieving helium did not behave as an ideal gas. The flow process also did not follow the classical isentropic process for a converging/diverging flow nozzle. The critical pressure ratio measured was below 0.2, as opposed to ideal/isentropic value of 0.5. This is shown for a 900 GeV quench in Figure 5. The pressure ratios shown in the figure all have the relief valve inlet static pressure (P_1) in the denominator. This is not technically the correct pressure to use; the total pressure (static pressure plus velocity head) is more appropriate. Velocities calculated at the inlet reassured us that the error introduced would not be significant. In any case, an actual total pressure would drive the pressure ratio slightly lower.

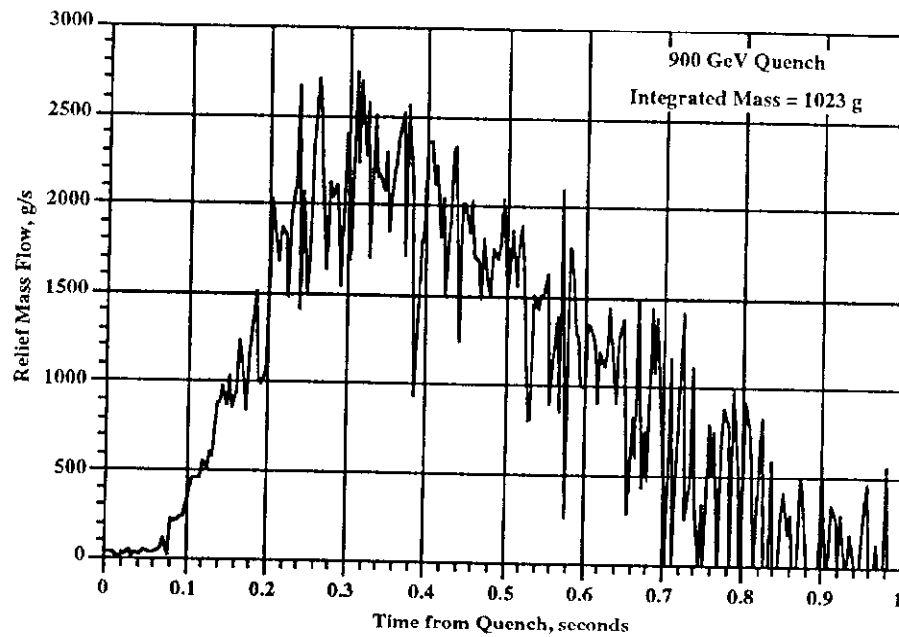


Figure 4. Relief mass flow versus time for a 900 GeV quench.

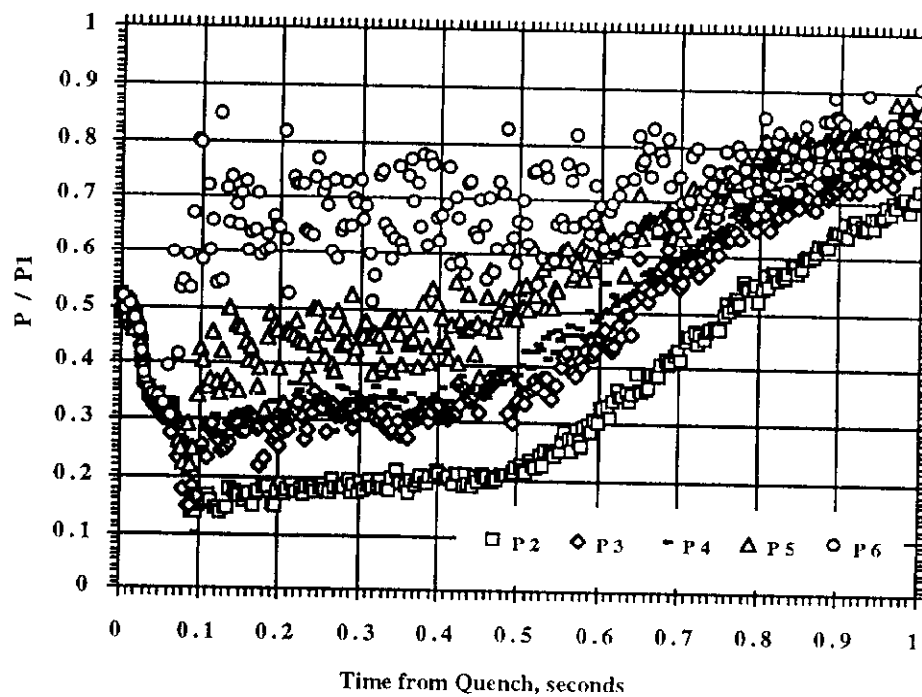


Figure 5. Reduced pressure ratios versus time for a 900 GeV quench. Reference Figure 1 and Table 1 for location of sensors.

Pressure ratios in the throat of the relief remained relatively constant near 0.2 during sonic flow conditions. It is speculated that the knee in the curves near 0.5 seconds represents the point where the valve goes subsonic. Higher pressure ratios suggest that the shock wave always occurred before reaching sensor P3. The Pitot tube total pressure sensor (P6) shows that there is considerable (~30%) loss in total pressure during sonic flow. For an ideal/isentropic process, total pressure is conserved, except for the loss directly across the shock wave. Limited pressure recovery near 1 second, where a shock wave should not be present, suggests that less than half of the loss could be associated with the shock wave. Non adiabatic flow, frictional losses and non ideal gas behaviors all would contribute to the remaining loss.

An attempt was made to reproduce the data using isentropic principles and real helium properties. Calculations were made starting at the relief valve inlet and working towards the Pitot tube as well as the reverse direction. The process was greatly complicated by the throat of the valve being in the two-phase regime. Although the exercise helped us to understand the general process, we failed at achieving any closure in the data.

CONCLUSIONS AND RECOMMENDATIONS

The test results show that the existing cryostats and relieving systems in the Tevatron will be sufficient for the new low temperature upgrade. Further studies will be required to investigate energies between 1000 and 1100 GeV.

Further studies would benefit from relief valve inlet temperature and flow measurements. A second data acquisition system would allow for the additional data without requiring multiple quenches. All temperature measurements would benefit from the ability to prefire the relief valve prior to ramping to full energy and inducing the quench. This precooling would further reduce the response time of the diodes to well before the time of peak mass flow.

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